PROGRESS AND CHALLENGES TO NDE OF COMPOSITES USING OBLIQUELY INSONIFIED ULTRASONIC WAVES

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Abstract
The leaky Lamb wave (LLW) technique is approaching a maturity level that is making it an attractive quantitative NDE tool for composites and bonded joints. Since it was first observed in 1982, the phenomenon has been studied extensively, particularly in composite materials. The wave is induced by oblique insonification using a pitch-catch arrangement and the resulting modes are acquired by identifying minima in the reflected spectra. These modes are documented in the form of dispersion curves, which are evaluated in relation to analytical data. The wave behavior in multi-orientation laminates has been well documented and corroborated experimentally with high accuracy. The sensitivity of the wave to the elastic constants of the material and to the boundary conditions led to the capability to measure the elastic properties of bonded joints. Recently, the authors significantly enhanced the experimental capability that is associated with the LLW technique by increasing the speed of the data acquisition and the number of modes that can be identified. This capability enables greater accuracy of the data inversion as well as improves the flaw characterization. In spite of the theoretical and experimental progress, methods that employ oblique insonification of composites are still not being applied as standard industrial NDE. The authors investigated the possible causes that are hampering the transition of the LLW to industrial application and identified 4 key issues. The recent development of the experimental capability and the issues that are affecting the transition of the technique to practical use are described in this paper.

Key Words: Leaky Lamb Waves (LLW), NDE, Composites, Stiffness Constants, Plate Wave Modes

1.0 Introduction

The high stiffness to weight ratio, low electromagnetic reflectance and the ability to embed sensors and actuators have made fiber-reinforced composites an attractive construction material for primary aircraft structures. These materials consist of fibers and a polymer matrix that are stacked in layers and then cured. A limiting factor in widespread use of composites is their high cost - composite parts are about an order of magnitude more expensive than metallic parts. The cost of inspection is about 30% of the total cost of acquiring and operating composite structures. This large portion of the total cost makes the need for effective inspection critical not only to operational safety but also to the cost benefit of these materials [Bar-Cohen, et al, 1991]. As we approaching the new millennium it is interesting to bookmark the challenge to NDE of composite materials and they include the following:

Defect Detection and Characterization: Throughout their life cycle composites are susceptible to the formation of many possible defects mostly due to the multiple step production process and their non-homogeneity with brittle matrix. These defects include delaminations, cracking, fiber fracture, fiber pullout, matrix cracking, inclusions, voids, and impact-damage. Table 1 lists some of the defects that may appear in composite laminates and their effect on structural performance. While the emphasis of most practical NDE is on detection of delaminations, porosity and impact damage, Table 1 shows that other defects can also have critical effect on host structures. Therefore, it is essential to be able to characterize the flaws in order to determine their degradation effect on the structural integrity.

TABLE 1: Effect of defects in composite materials

Defect	Effect on the material performance
Delamination	Catastrophic failure due to loss of interlaminar shear carrying capability. Typical acceptance criteria require the detection of delaminations that are $\geq$0.25-inch.
Impact damage	The effect on the compression static strength • Easily visible damage can cause 80% loss • Barely visible damage can cause 65% loss
Ply gap	Degradation depends on stacking order and location. For $[0,45,90,-45]_{2S}$ laminate: - 9% strength reduction due to gap(s) in 0° ply - 17% reduction due to gap(s) in 90° ply
Ply waviness	• Strength loss can be predicted by assuming loss of load-carrying capability. • For 0° ply waviness in $[0,45,90,-45]_{2S}$ laminate, static strength reduction is: - 10% for slight waviness - 25% for extreme waviness • Fatigue life is reduced at least by a factor of 10
Porosity	• Degrades matrix dominated properties • 1% porosity reduces strength by 5% and fatigue life by 50% • Increases equilibrium moisture level • Aggravates thermal-spike phenomena
Surface notches	• Static strength reduction of up to 50% • Local delamination at notch • Strength reduction is small for notch sizes that are expected in service
Thermal Over-exposure	Matrix cracking, delamination, fiber debonding and permanent reduction in glass transition temperature

Material Properties Characterization: Production and service conditions can cause property degradation and sub-standard performance of primary structures. Sources for such degradation can be the use of wrong constituent (fiber or matrix), excessive content of one of the constituent (resin rich or starved), wrong stacking order, high porosity content, micro-cracking, poor fiber/resin interface aging, fire damage, and excessive environmental/ chemical/radiation exposure. Current destructive test methods of determining the elastic properties are using representative coupons. These methods are costly and they are not providing direct information about the properties of represented structures.

Rapid Large Area Inspection: Impact damage can have critical effect on the capability of composite structures to operate in service. This critical flaw type can be induced during service life anywhere on the structure and it requires detection as soon as possible rather than waiting for the next scheduled maintenance phase. Using conventional NDE for the assurance of the structural integrity can be very expensive and takes aircraft out of their main mission. Since impact damage can appear anytime and anywhere on the structure, there is a need for a low-cost system that can be used to rapidly inspect large areas in field condition. The use of a robotic crawlers can potentially offer effective platform for rapid inspection of composite structures [Bar-Cohen and Backes, 1999].

Real-Time Health Monitoring: Structurally integrated health monitoring systems are needed to reduce the need for periodic inspection and temporal removal of aircraft from service. Fundamentally, such health monitor systems emulate biological systems where onboard sensors track the structural integrity throughout the life cycle. Such systems can monitor changes in the characteristics of critical parameters and activate an alarm when certain values are exceeded.

Smart Structures: The availability of compact actuators, sensors and neural networks has made it possible to develop structures that self-monitor their own integrity and use actuators to avoid or timely respond to threats. The changing environment or conditions can be counteracted by adequate combination of actuators and sensors that change the conditions and/or dampen the threat. Sensor fusion, neural network and other artificial intelligence capabilities can be used to assure quickly making the most effective response. An example of the application of smart structures is the reduction of vibrations that lead to fatigue.

Residual Stresses: Current state of the art does not provide effective means of nondestructive determination of residual stresses. Technology is needed to detect and relieve residual stresses in structures made of composite materials.

Weathering and Corrosion Damage: Composites that are bonded to metals are sensitive to exposure to service fluids, hygrothermal condition at elevated temperatures and to corrosion. Particular concern rises when aluminum or steel alloys are in a direct contact with composites that consist of graphite fibers or carbon matrix. Graphite is cathodic to aluminum and steel and therefore the metal, which is either fastened or bonded to it, is eroded. In the case of graphite/epoxy the metal deteriorates, whereas in the case of graphite/polyimide defects are induced in the composite with the form of microcracking, resin removal, fiber/matrix interface decoupling and blister (e.g. delaminations). The level of degradation of composite materials exposed to service environment depends on the chemical structure of the polymer matrix. In thermoset composites, the epoxy absorbs moisture and loses its thermal stability as a matrix in a reversible plasticisation process. On the other hand, thermoplastics are susceptible to effects of aircraft fluids such as cleaning fluids, paint stripping chemicals and fuel. Imide polymers are sensitive to strong base producing amid acid salts and amides, and their degradation rate is determined by such parameters as the temperature, stress, and humidity. The strength of the material deteriorates at an exponential rate, however annealing can reduce the degradation rate.

Generally, NDE methods are used to determine the integrity and stiffness of composite structures. While information about the integrity and stiffness can be extracted directly from NDE measurements, strength and durability can not be measured by such measurements because these are not physically measurable parameters. For many years, the multi-layered anisotropic nature of composites posed a challenge to the NDE research community. Pulse-echo and through-transmission are still the leading standard NDE methods of determining the quality of composites.

However, these methods provide limited and mostly qualitative information about defects and material properties. The discovery of the leaky Lamb wave (LLW) [Bar-Cohen & Chimenti, 1984] and the Polar Backscattering [Bar-Cohen & Crane, 1982] phenomena in composites enabled effective quantitative NDE of composites. These obliquely insonified ultrasonic wave techniques were studied both experimentally and analytically by numerous investigators [e.g., Mal & Bar-Cohen, 1988, Nayfeh & Chimenti, 1988, and Dayal & Kinra, 1991]. These studies led to the development of effective quantitative NDE capabilities for the determination of the elastic properties, to an accurate characterization of defects and even the determination of the quality of adhesively bonded joints [Bar-Cohen, et al, 1989]. In spite of the progress that was made both theoretically and experimentally, oblique insonification techniques have not yet become standard industrial NDE methods for composite materials. The authors investigated the possible causes that are hampering the transition of the LLW technique to practical NDE and address the key issues that are associated with the experimental capability.

2.0 Leaky Lamb Wave Phenomenon

The leaky Lamb wave (LLW) phenomenon is induced when a pitch-catch ultrasonic setup insonifies a plate-like solid immersed in fluid [Bar-Cohen, Mal and Lih, 1993]. This phenomenon was discovered by the principal author in August 1982 while testing a composite laminate using Schlieren imaging system (see Figure 1). The phenomenon is the result of a resonant excitation of plate waves that leak waves into fluid medium and interfere with the specular reflection. The LLW phenomenon modifies the reflection spectrum introducing a series of minima associated with the excitation of plate wave modes. These minima are the result of a destructive interference at the specific frequencies between the leaky and the spectral reflection. The LLW experimental procedure involves measurement of the reflections and extraction of the dispersive spectral characteristics at various angles of incidence and along several orientations with the laminate fibers. The data is presented in the form of dispersion curves showing the LLW modes phase velocity (calculated from Snell's law and the angle of incidence) as a function of the frequency.

Following the LLW discovery, a study was conducted by [Bar-Cohen and Chimenti, 1984] who investigated the characteristics of the LLW phenomenon and its application to NDE. These investigators concentrated on the experimental documentation of observed modes and the effect of defects. Their study was followed by numerous other investigations of the phenomenon [e.g., Nayfeh & Chimenti, 1988, Mal & Bar-Cohen, 1988, and Dayal & Vikram, 1991]. In 1987, [Mal, 1988] developed a model that can be used to accurately predict the wave behavior and the results were corroborated experimentally. Later a method was developed to invert the elastic properties using the LLW dispersion data [Mal & Bar-Cohen, 1988] and the study was expanded to NDE of bonded joints [Bar-Cohen, et al, 1989].

The experimental acquisition of dispersion curves for composite materials requires accurate control of the angle of incidence/reception and the polar angle with the fibers. The need to perform these measurements rapidly and accurately was addressed at JPL where a specially designed LLW scanner was developed [Bar-Cohen, Mal & Lih, 1993]. With the aid of a personal computer, this scanner (made by QMI, Costa Mesa, CA) controls the height, angle of incidence and polar angle of the pitch-catch setup. The LLW scanner controls the angle of incidence/reception simultaneously while maintaining a pivot point on the part surface. A view of the LLW scanner installed on a C-scan unit is shown in Figure 2. A computer code was written to control the incidence and polar angles, the height of the transducers from the sample surface, and the transmitted frequency. In prior studies, the data acquisition involved the use of sequentially transmitted tone-bursts at single frequencies over a selected frequency range (within the 20dB level of the transducer pair). Reflected signals are acquired as a function of the polar and incidence angle and are saved in a file for analysis and comparison with the theoretical predictions. The minima in the acquired reflection spectra represent the LLW modes and are used to determine the dispersion curves (phase velocity as a function of frequency). The incident angle is changed incrementally within the selected range and the reflection spectra are acquired. For graphite/epoxy laminates the modes are identified for each angle of incidence in the range of 12° to 50° allowing the use of free-plate theoretical calculations. At each given incidence angle, the minima are identified and are added to the accumulating dispersion curves, and are plotted simultaneously on the computer display. While the data acquisition is in progress, the acquired minima are identified on both the reflection spectra and the dispersion curves.

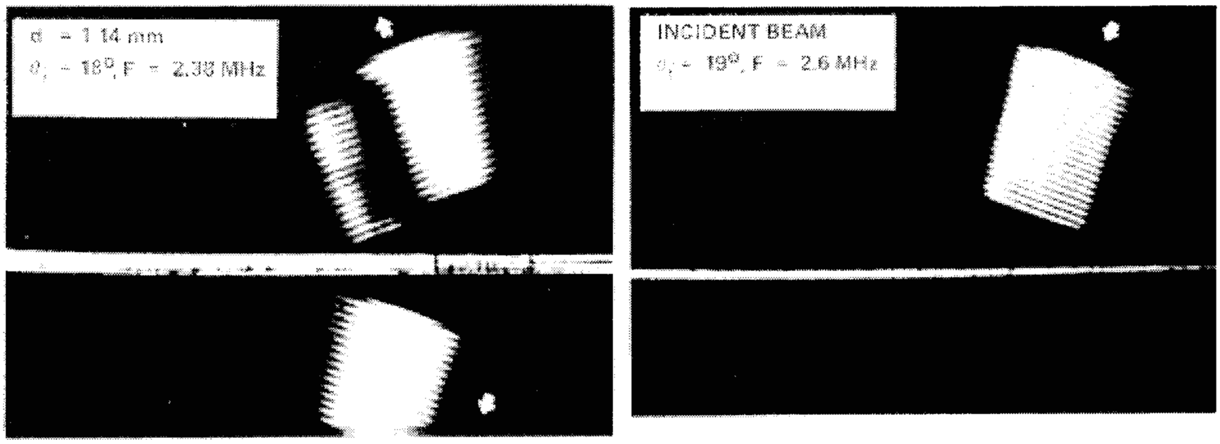


FIGURE 1: A Schlieren image of the LLW phenomenon showing a tone-burst before and after impinging on the graphite/epoxy laminate.

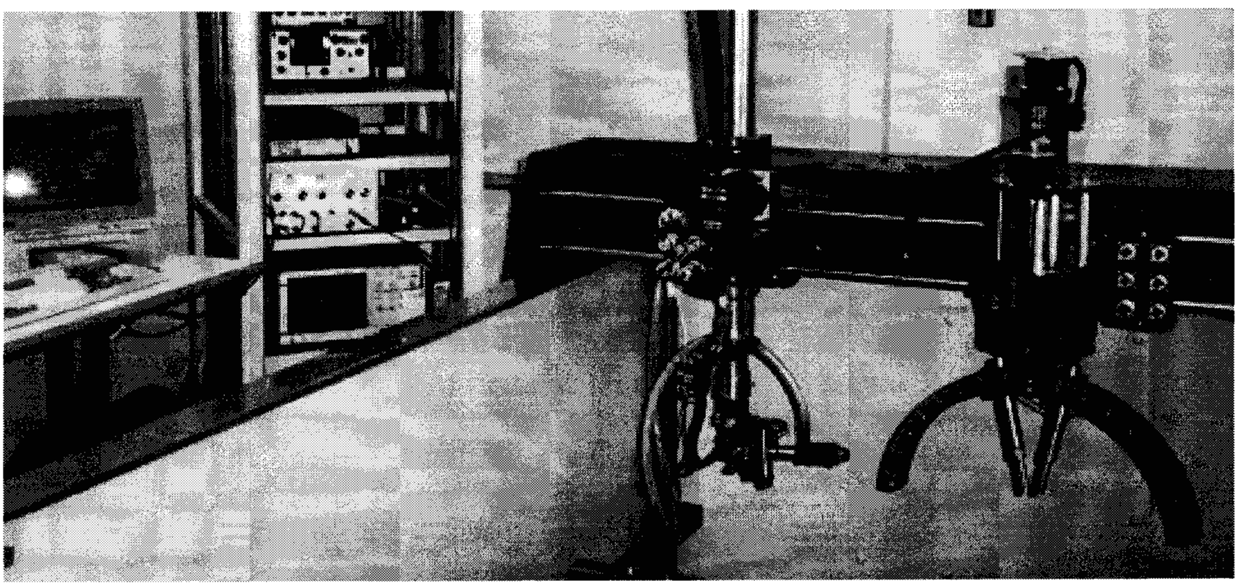


FIGURE 2: A view of the LLW scanner (bridge right side) installed on the JPL's C-scan system

A follow-on study by [Bar-Cohen, Mal & Lih 1993] showed that the capability to invert the elastic properties using LLW data is limited to the matrix dominated stiffness constants. To overcome this limitation, which is associated with the need for angles of incidence as small as 8^{o}, a methodology was developed that is based on using ultrasonic pulses. Assuming that the material is transversely isotropic and using pulses in pitch-catch and pulse-echo experimental arrangements, it was shown that all the five elastic constants can be determined fairly accurately. A parametric study was conducted and the expected error was determined for the various determined constants in relation to experimental errors. It was also shown that, C_{12}, the constant with the most sensitivity to defects, is critically sensitive to alignment errors in the incident and polar angles. While this capability allowed measuring dispersion curves to support the analytical efforts, the process has been still slow and there were difficulties identifying modes that were associated with small minina, which is lower than about 4% of the adjacent signal.

3. 0 Rapid LLW Dispersion Data Acquisition

The analytical modeling of the behavior of an ultrasonic wave that is propagating through a composite material has been well documented by many researchers, particularly for unidirectional composite laminates [see for example: Bar-Cohen, Mal and Lih, 1993]. The authors identified a series of experimental deficiencies that affecting the inversion reliability and the transition of the LLW technique to practical application. Their recent efforts concentrated on the enhancement of the speed of the data acquisition and the number of modes that can be identified in the experiment. A schematic view of the test system is shown at the center of Figure 3. Since the process of acquiring the spectrum was identified as time consuming with a series of redundancies, it was modified to FM modulated transmitted pulses that are induced sequentially within the required spectral range. The function generator also provides a reference frequency marker for the calibration of the data acquisition when converting the signal from time to frequency domain. A digital scope is used to acquire the reflection spectral data after being amplified and rectified by an electronic hardware. The signals that are induced by the transmitter are received, processed and analyzed by a personal computer after being digitized. The reflected spectra for each of the desired angles of incidence is displayed on the monitor and the location of the minima (LLW modes) are marked by the computer on the reflection spectrum. The algorithm of identifying the minima was modified to provide smaller levels that are associated with more diffused modes. The identified minima are accumulated on the dispersion curve, which is shown on the lower part of the display (see Figure 4). The use of the FM modulation approach enabled a significant increase in the speed of acquiring dispersion curves. To compare the performance, 20 different angles of incidence were acquired in about 45 seconds as oppose to over 15-minutes using the former approach. An algorithm that is based on the Simplex inversion methodology was already programmed into the computer software and was used to extract the stiffness constants. Once the dispersion data is acquired, the inversion option of the software is activated and the elastic stiffness constants are determined as shown in Figure 4. Typical LLW dispersion data and inverted results for a unidirectional graphite/epoxy plate were shown in Figure 4. The material is AS4/3501-6 and the polar angle (i.e., the direction of Lamb wave propagation) is 0^{o}. The reflected spectrum for 39.9^{o} incident angle is shown at the top of this Figure, and the accumulating dispersion curves are at the bottom. The inverted elastic and stiffness constants are given at the left.

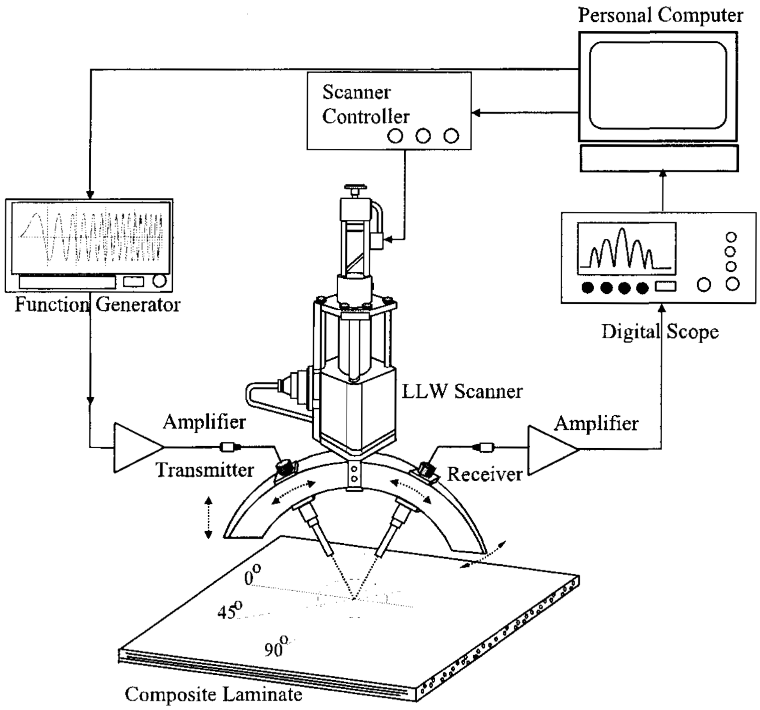


FIGURE 3: A schematic view of the rapid LLW test system.

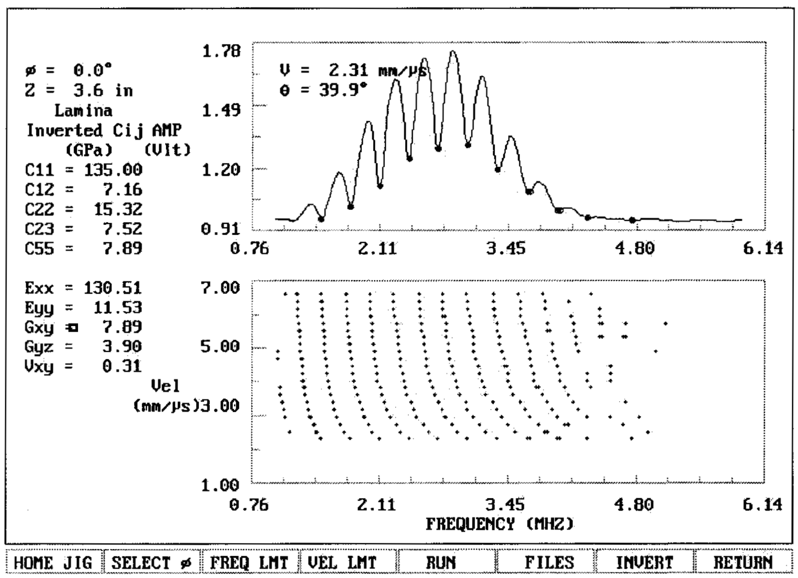
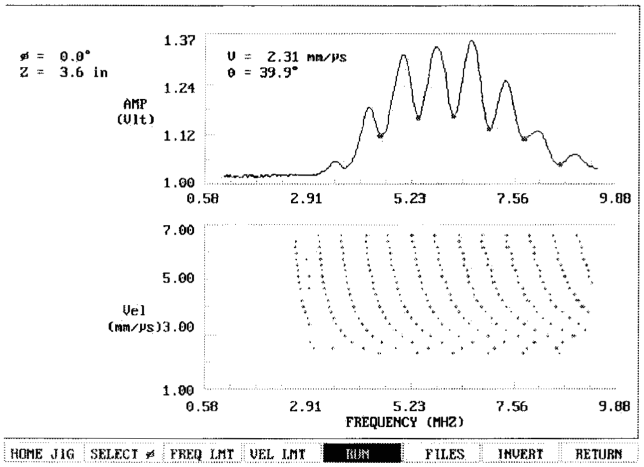


FIGURE 4: Computer display after the data acquisition and inversion completion. The elastic stiffness constants are inverted from the dispersion curve and are presented on the left of the screen.

Using the system with the enhanced data acquisition speed, various defects can be detected and characterized based on the signature and quantitative data that is available from the dispersion curves. In Figure 5a, the response from a defect-free graphite/epoxy laminate tested at the 0-degree polar angle is shown. In Figure 5b, the response from an area with a layer of simulated porosity (microballoons) is presented. As expected, at low frequencies the porosity has a relatively small effect and the dispersion curve appears similar to the one on Figure 5a. On the other hand, as the frequency increases, the porosity layer emulates a delamination and modifies the dispersion curve to appear the same as half the thickness laminate.



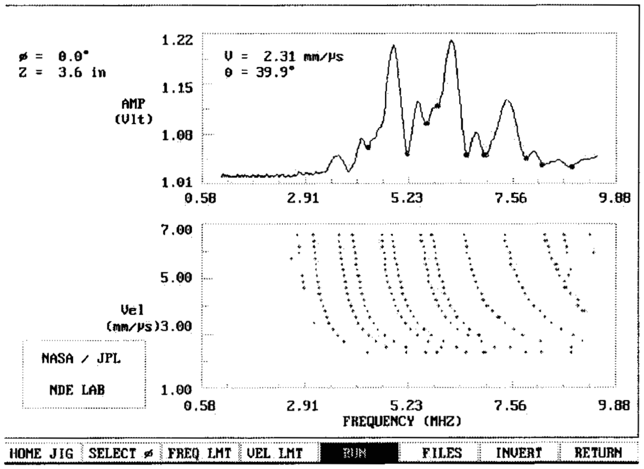


FIGURE 5a: The refection at 39.5 degrees incidence angle and the dispersion curve for a Gr/Ep $[0]_{24}$ laminate with no defects

FIGURE 5b: The response at a defect area where porosity was simulated at the middle layer.

To demonstrate the capability of the LLW method to characterize material degradation of composites, a sample made of AS4/3501-6 $[0]_{24}$ laminate was tested after it was subjected to heat treatment. The sample was exposed to a heat ramp from room temperature to 480° F for 15 minutes, and then was taken out of the oven to cool in open air at room temperature. The sample was tested at a specific location before and after heat treatment. The measured dispersion curves are shown in Figure 6. It can be seen that there are distinct differences in the dispersion data for the specimen before and after heat treatment. Since the heat damage occurs mostly in the matrix, the effect is expected to be more pronounced in the matrix dominated stiffness constants. The constants c_{11}, c_{12}, c_{22}, c_{23} and c_{55} obtained from the inversion process are 127.9, 6.32, 11.85, 6.92 and 7.43 GPa, before heat treatment, and 128.3, 6.35, 10.55, 6.9 and 7.71 GPa, after heat treatment. The most noticeable and significant change is in the stiffness constant c_{22}, which is the property most sensitive to variations in the matrix resulting in a reduction in the transverse Young's modulus.

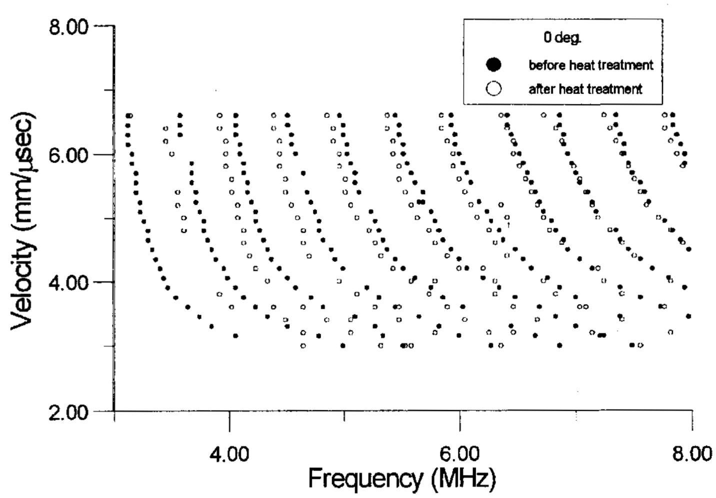


FIGURE 6: The measured dispersion curves of a $[0]_{24}$ graphite-epoxy panel before and after heat treatment.

4.0 Multiplexed LLW System

The basic setup of the LLW data acquisition system was shown photographically in Figure 2 and schematically in Figure 3, where the angle of a pair of transducers is physically changed in steps. This motion places a practical limit on the speed of dispersion data acquisition, which was demonstrated to be in the range of 45 seconds using our recent modification. To make the data acquisition process faster the use of electronic scanning can be the next alternative. A multiplexing system was developed as shown schematically in Figure 7, where a pair series of pitch-catch ultrasonic transducers was developed with the transducers directed toward a selected point on the top surface of the tested composite laminate. The data acquisition flow chart diagram is also shown in Figure 7 and the signals that are induced by the transmitter are received, processed and analyzed by a personal computer after being digitized. The developed software activates sequentially the various transducer pairs that are triggered for data acquisition. Signals are induced by FM modulated function generator, as described earlier, and are received by a set of receiver/amplifier after interrogating the test area. This multiplexed system of transducer pairs was also designed as an attachment added-on to ultrasonic C-scanners. The multiplexed transducer fixture is shown photographically in Figure 8.

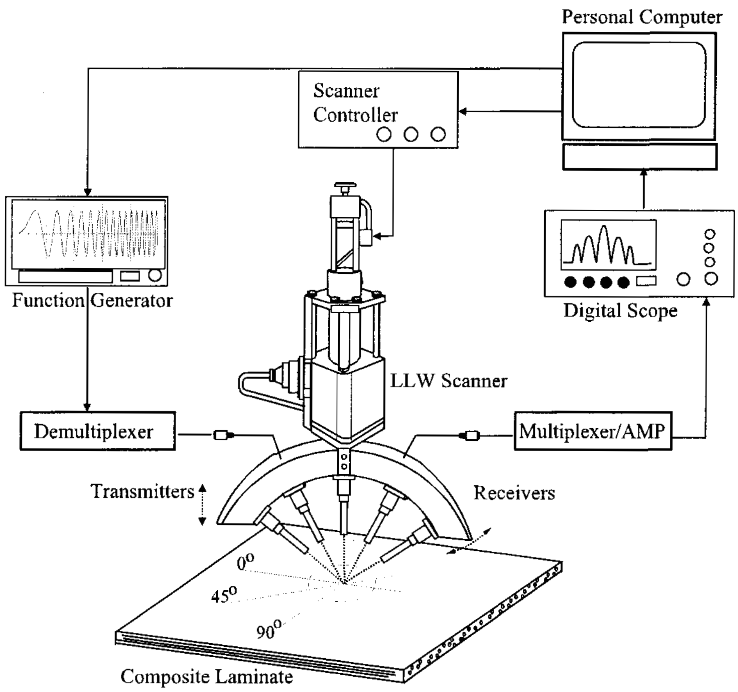


FIGURE 7: A schematic view of the multiple pairs of transducers system that are scanned electronic for testing composite material.

A system of 4 pairs of 5MHz transducers was used, which were aligned to transmit at 15, 30, 45 and 60 degrees angles of incidence. A multiplexer was designed to triggering the data acquisition of the selected transducer pair. The data acquisition setup consisted of a pulse generator HP 8116A, broadband receiver (Matec Model 605), amplifier (Panametrics Model 5052UA) and digital scope (LeCroy 9410 series dual 150 MHz oscilloscope). The digital scope displays the reflection spectrum in real time and a PC displays a user menu that controls the data acquisition and analysis operation. Further, the computer program was modified to automatically control the sequence of activated transducer pairs and the acquisition of the dispersion curve. Each pair represents a given angle of incidence and the acquired data is display on the screen. Again, the computer marks the minima of the reflection spectrum (LLW modes) and the minima are accumulated separately to form a dispersion curve. Once the dispersion data is ready, the software option of data inversion is activated and the elastic stiffness constants are determined.

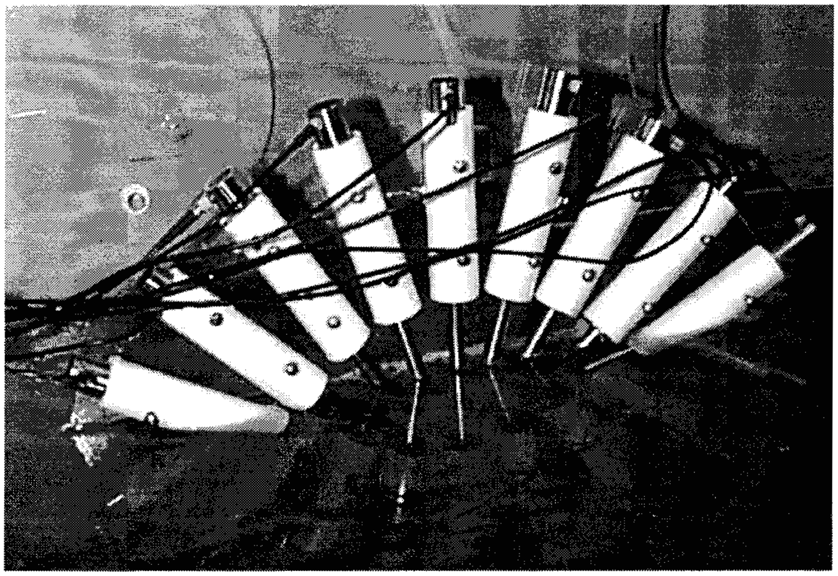


FIGURE 8: A view of the multi-probe system.

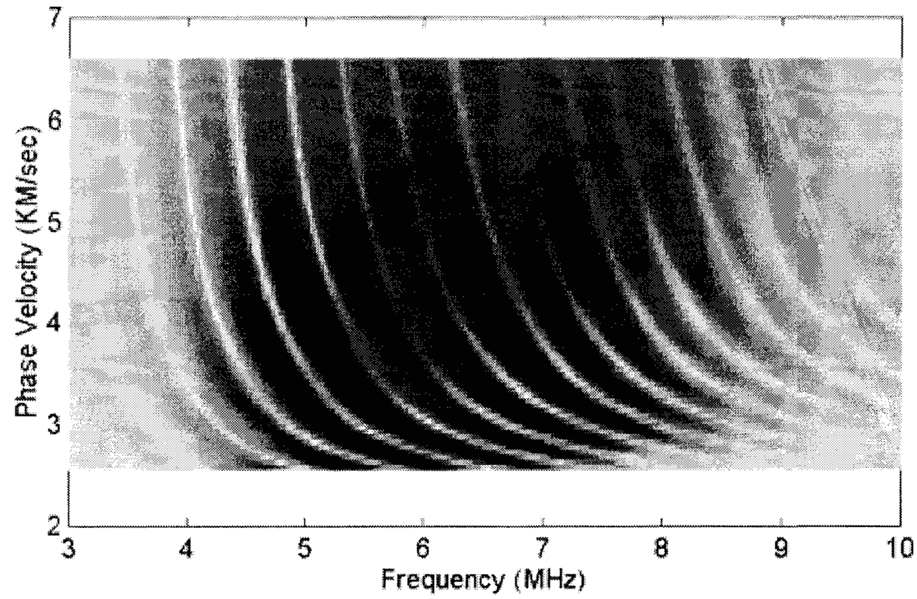


FIGURE 9: A view of an imaging method of presenting LLW dispersion curve for unidirectional Gr/Ep along the fibers.

5.0 Enhanced Dispersion Curve Modes Identification

To enhance the accuracy of the inversion of the material stiffness constants, a method was developed to acquire dispersion curves and display them in a graphics format as shown in Figure 9. This method was found to allow viewing modes with amplitude levels that are significantly smaller than those observed previously. The bright curved lines show the modes on the background of the reflected spectra. Methods of extracting the modes were investigated using image processing operators and neural network procedures. Once the curve of a specific mode is determined, it is transformed to actual frequency vs. velocity data and then inversion is applied. This process involves trade-off between noise suppression and localization, where an edge detection operator is used to reduce noise but involved added uncertainty to the location of the modes. Our approach consisted of using a linear operator that employs a first derivative Gaussian filter. This filter numerically approximated standard finite-difference for the first partial derivatives in the x and y directions. This type of operator is not rotationally symmetric and it is sensitive to the edge in the direction of steepest change, but acts as a smoothing operator in the direction along the edge.

6.0 Issues Affecting the Transition of LLW to Practical Use

After over 16 years since the discovery of the LLW phenomena the method and its being studied and well documented both analytically and experimental the technique is still not being used for practical NDE. The authors examined the issues that may hamper the transition of the LLW method to standard NDE application and identified the following possible issues:

1. Material density - The inverted material constants assume that the material density is known. NDE measurement of the material density can be done by radiographic tests. However, such tests are not economical and they require access from two sides of the test structure, therefore an alternative method of measuring the density is needed.
2. Multi-orientation laminates - The inversion algorithm developed for the determination of the elastic properties has been very successful for unidirectional laminates. The analysis of laminates with multi-orientation layers using ply-by-ply analysis is complex and leads to ill-posed results. Methods of inverting the material elastic properties without the necessity to deal with individual layers are currently being explored.
3. Complex data acquisition - The LLW data acquisition setup is complex and the related process is not user friendly. The authors have significantly improved the data acquisition process, where a personal computer assists the user by optimizing the setup height to assure the greatest ratio between the maximum and minimum amplitudes in the reflected spectrum. The polar angle is set using the polar backscattering technique [Bar-Cohen and Crane, 1982] to determine the direction of the first layer. Further, user friendly control software that operates on the Widows platform is being developed to allow interactive software control.
4. Time-consuming process - The formerly reported process of acquiring a dispersion curve was time consuming and took between 10 and 20 minutes to acquire a curve for a single point on the composite material. As reported in this manuscript, recent development by the authors allows the measurement of the dispersion curves at a significantly higher speed in the range of fraction of a minute. Using this new capability, various defects can be detected and characterized based on their dispersion curve signature. Further, this increased speed of dispersion data acquisition offers the capability to produce C-scan images where variations in individual stiffness constants can be mapped.

7.0 Conclusions

The leaky Lamb wave (LLW) method has been studied by numerous investigators who contributed significantly to the understanding of wave behavior in anisotropic materials. However, in spite of this progress, the LLW method is still far from being an acceptable standard NDE method. The authors investigated the potential issues that are hampering this transition to practical NDE and identified 4 key issues: a) There is a need to determine the density nondestructively using access from a single-side; b) The technique should be applicable to multi-layer angle-ply composites; c) The data acquisition process needs to be more user friendly; and d) The process of data acquisition needs to be more rapid. The authors have made significant progress in the simplification of the data acquisition process and the acquisition speed with some progress being made in dealing with cross-ply and quasi-isotropic laminates. The inability to measure the material density with an NDE tool using access from a single side of a laminate is still considered an unresolved issue and will require further research.

8.0 Acknowledgment

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